Effect of Injection Pressure and Size of Nozzle Throat of a Cavitating Jet on Cavitation Peening

H. Soyama[1], O. Takakuwa[1] and A. Naito[1]

1 Department of Nanomechanics, Tohoku University, Japan

Abstract
Cavitation peening is a peening method using impacts at cavitation bubble collapses generated by a cavitating jet. In order to introduce compressive residual stress avoiding damage on the peened surface, residual stress of stainless steel was investigated at various cavitating conditions. It was revealed that the large cavitating jet at low injection pressure such as 30 MPa can introduce larger compressive residual stress into deeper region comparing of small cavitating jet at high injection pressure such as 300 MPa.

Keywords Residual stress, Cavitation, Jet, Stainless steel.

Introduction
Cavitation impact normally causes severe erosion in hydraulic machineries such as pump and valves. However, it can be utilized for peening to improve materials properties of metallic materials such as fatigue strength in stead of shot peening. A peening method using cavitation impact is named as “cavitation peening”. In the case of the cavitation peening, cavitation is normally generated by injecting a high-speed water jet into a water-filled chamber, i.e., a cavitating jet. The introduction of compressive residual stress using the cavitating jet was proposed by Soyama et al. [1], and it was confirmed [2]. Now, it has been applying to nuclear power plants to mitigate stress corrosion cracking [3]. The improvement of fatigue strength by cavitation peening was also reported [4-9]. As aggressivity of the cavitation is affected by injection pressure and size of the nozzle throat for the cavitating jet, it is required to clarify the effect of the injection pressure and the size of the nozzle on cavitation peening.

The type of cavitation induced by the cavitating jet is vortex cavitation. When the injection pressure and/or the size of nozzle throat are increased, the vortex cavitation is developed, as Reynolds number at the nozzle is increased. The large vortex cavitation can produce big impact and then the peening effect by large vortex cavitation will be effective. In the view point of Reynolds number, the effect of the injection pressure, i.e., the flow velocity, and the size of the nozzle throat have same effect. However, the other main parameter of the cavitating jet, i.e., cavitation number, is changed by the injection pressure. It was reported that the optimum cavitation number exist on the aggressivity of the cavitating jet [11]. When the downstream pressure of the nozzle throat is constant, the cavitation number is decreased. This means that the aggressivity of the cavitating jet of too high injection pressure is getting weak with an increase of the injection pressure. On the other hand, the aggressivity will be increased with size of the nozzle throat because of scaling effect of the cavitation.

In the present paper, in order to clarify the effect of the injection pressure and nozzle size of the cavitating jet, the introduced compressive residual stress was investigated by using cavitating jets at various conditions.

Experimental Facilities and Procedures
Figure 1 shows a cavitating jet apparatus for cavitation peening. The high speed water jet pressurized a plunger pump was injected into water filled tank A through test nozzle. Two types of plunger pumps were used. The maxim injection pressure p_1 and maximum flow rate

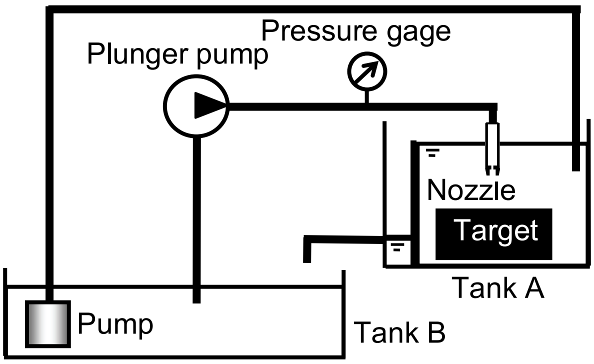
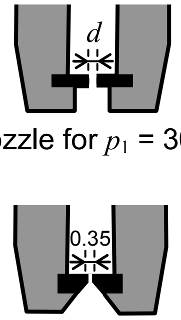


Fig. 1 Schematic diagram of apparatus for cavitating jet



(a) Nozzle for p_1 = 30 MPa

(b) Nozzle for p_1 = 300 MPa

Fig. 2 Nozzle geometry

Q were 300 MPa and 3.4 × 10^{-3} m^3/min, 30 MPa and 3.0 × 10^{-2} m^3/min, respectively. The nozzle geometry was shown in Fig. 2. In the case of nozzle for p_1 = 30 MPa, the optimum nozzle outlet geometry, which was revealed in our previous report [12], was used in the present experiment. In order to investigate scaling effect of cavitating jet, the nozzle throat diameter d = 0.35, 0.6, 1, 1.5 and 2 mm were tested. As the diamond orifice should be placed in the nozzle throat for p_1 = 300 MPa, the nozzle as shown in Fig. 2 (b) was used considering previous results [12]. The throat diameter of the nozzle for p_1 = 300 MPa was fixed as 0.35 mm.

The processing time per unit length, t_p, was varied by changing the speed of the nozzle. t_p was determined using the number of scans, n, and the scanning speed, v, as follows:

$$t_p = \frac{n}{v} \quad (1)$$

Tested material for measurement of residual stress was Japan Industrial Standard JIS SUS316L. The residual stress was measured by X-ray diffraction methods, i.e., $\sin^2\psi$ method and 2D method. In the case of $\sin^2\psi$ method, a Cr tube, operating at 30 kV and 8 mA, was used to produce Kβ X-rays. X-rays were counted using a scintillation counter at angles ψ = 0, 22.8, 33.2, 42.1 and 50.7 deg. Here, ψ is the angle between the normal to the specimen surface and the normal to the diffractive lattice plane. The diffractive lattice plane *h k l* was (3 1 1) of γ-Fe. The stress factor was -369.5 MPa/deg. The distribution of residual stress with distance from surface, z, was obtained by electrolytic polishing and X-ray diffraction. In the case of 2D method, the other Cr tube, operating at 35 kV and 40 mA, was used to produce Kα X-rays and X-rays were counted 21 frames using a 2D detector at various angle.

It was reported in the previous report [13] that the residual stress σ_R on the surface introduced by cavitation peening can be described by following equation considering stochastic occurrence of the cavitation impacts,

$$\sigma_R = (\sigma_{sat} - \sigma_0)(1 - e^{-a t_p}) + \sigma_0 \quad (2)$$

where σ_{sat} and σ_0 are saturation value and initial value of the residual stress, respectively. a is the constant and it identifies the frequency of the impact.

In order to investigate distribution of impact force, cavitation impacts induced by the cavitating jet were evaluated by an impact sensor with PVDF (Polyvinylidene Fluoride) film [13, 14]. using the impact energy per unit time, E, related to cavitation peening was summation of the square of the impact forces, F_i, that are larger than a threshold level, F_{th}, as follows. This detail is from the references [14, 15].

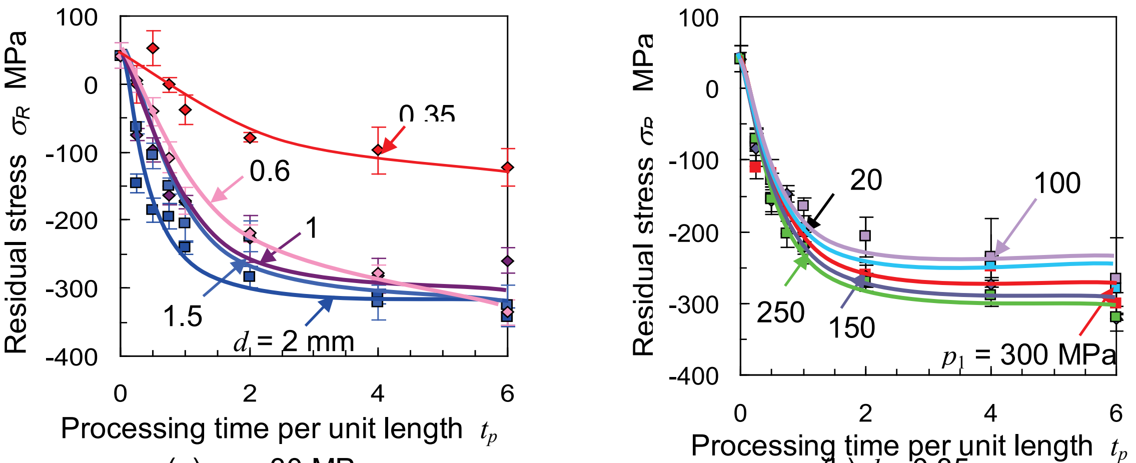
$$E = \frac{k \sum_{F_{th}} F_i^2}{\Delta t} \quad (3)$$

where k is a proportionality and Δt is unit time of the pulse measurement.

Experimental Results

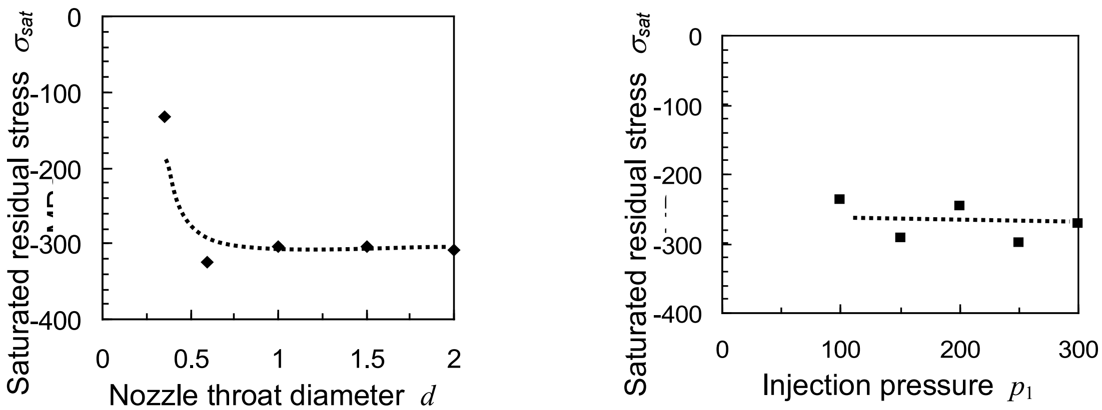
Figure 3 shows residual stress on the surface of the stainless steel as a function of processing time per unit length t_p at various p_1 and d. The stainless was treated at optimum standoff distance at each condition. In the case of p_1 = 30 MPa, d was changed from 0.35 mm to 2 mm. At d = 0.35 mm, the introduced compressive residual stress was considerably smaller than the other cases. From d = 0.6 mm to d = 2 mm, although the saturated residual stress was nearly same, the time to reach saturated stress at d = 2 mm was quicker than that of d = 0.6 mm. On the other hand, the time and the saturated stress from p_1 = 100 MPa to 300 MPa were nearly same. As the jet power to inject the high speed water jet was proportional to product of the flow rate and the injection pressure, the jet power of p_1 = 300 MPa was 5.2 times larger than that of p_1 = 100 MPa. Thus, if the peening effect of p_1 = 100 MPa was equal to that of p_1 = 300 MPa, the jet at p_1 = 100 MPa should be used.

In order to investigate the saturated residual stress and the time to reach the saturated stress at various nozzle diameter and the injection pressure, the saturated stress σ_{sat} and constant a in Eq (2) were obtained using the results of Fig. 3. Figures 4 and 5 reveal σ_{sat} and



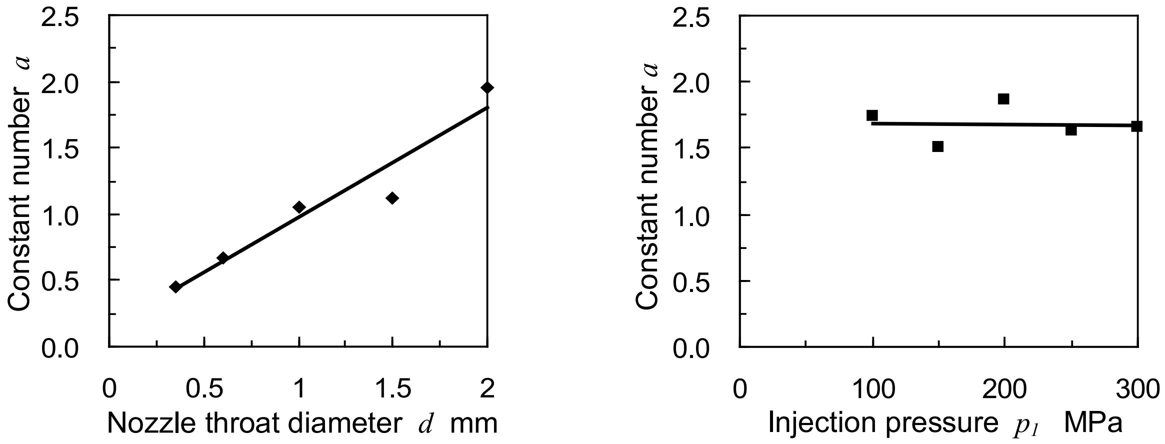
(a) p_1 = 30 MPa (b) d = 0.35 mm

Fig. 3 Residual stress as a function of processing time per unit length



(a) p_1 = 30 MPa (b) d = 0.35 mm

Fig. 4 Saturated residual stress at various nozzle diameter and injection pressure



(a) p_1 = 30 MPa (b) d = 0.35 mm

Fig. 5 Time to reach the saturated stress at various nozzle diameter and injection pressure

a, respectively. As shown in Fig. 4 (a), the saturated residual stress on the surface was nearly same except d = 0.35 mm, p_1 = 30 MPa. When the results of Fig. 4 (a) and (b) were compared, σ_{sat} of d = 0.35 mm, p_1 = 100 - 300 MPa were rather smaller than that of d = 0.6 - 2 mm, p_1 = 30 MPa. As shown in Fig. 5 (a), a was increasing with d. Namely, the time to reach saturate stress was decreased, when the cavitating jet through large nozzle throat diameter. On the other hand, a was nearly constant at p_1 = 100 - 300 MPa. In view point of peening at low cost, peening using the jet at low injection pressure would be better.

Figure 6 illustrates the residual stress as a function of depth from the surface. In Fig. 6, specimens were peened by the jet at d = 2 mm, p_1 = 30 MPa and d = 0.35 mm, p_1 = 300 MPa. At both cases, the jet power defined by the flow rate and the injection pressure was same. The processing time per unit length was 1 s/mm at both cases. The residual stress at the surface of d = 2 mm, p_1 = 30 MPa was -280 MPa, and the stress of d = 0.35 mm, p_1 = 300 MPa was -220 MPa. The jet of d = 0.35 mm, p_1 = 300 MPa can introduce compressive residual stress up to 300 μm. On the other hand, the residual stress of d = 2 mm, p_1 = 30 MPa was -140 MPa at 600 μm. Namely, the large cavitating jet at low injection pressure, such as 30 MPa can introduce larger compressive residual stress larger into deeper region.

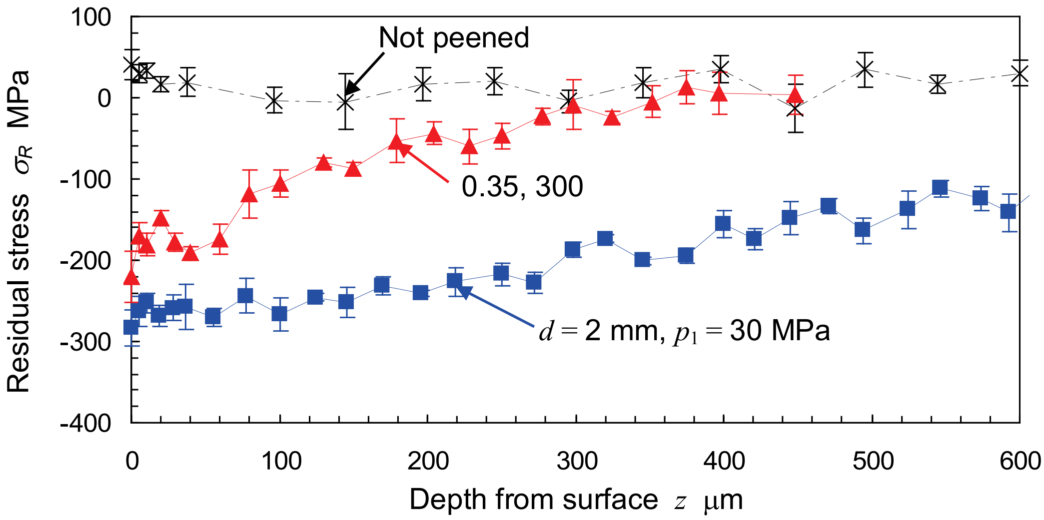


Fig. 6 Residual stress changing with depth

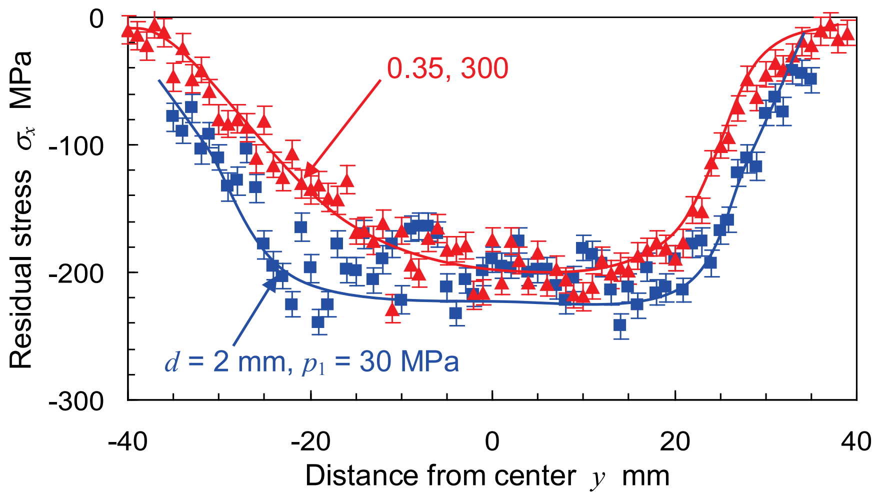


Fig. 7 Width of peening area

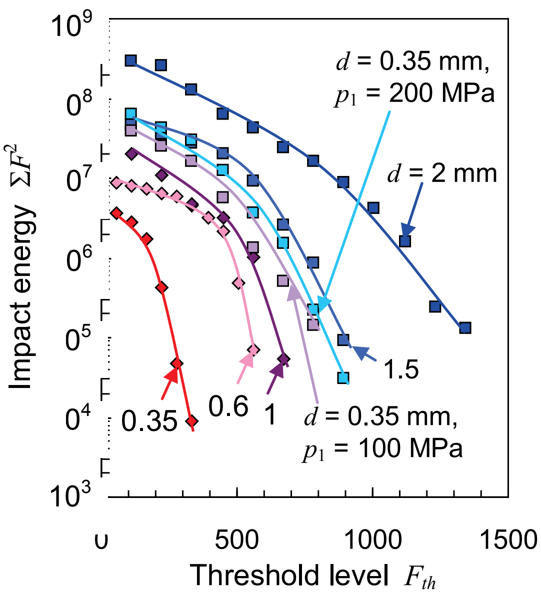


Fig. 8 Distribution of impact energy as a function impact intensity

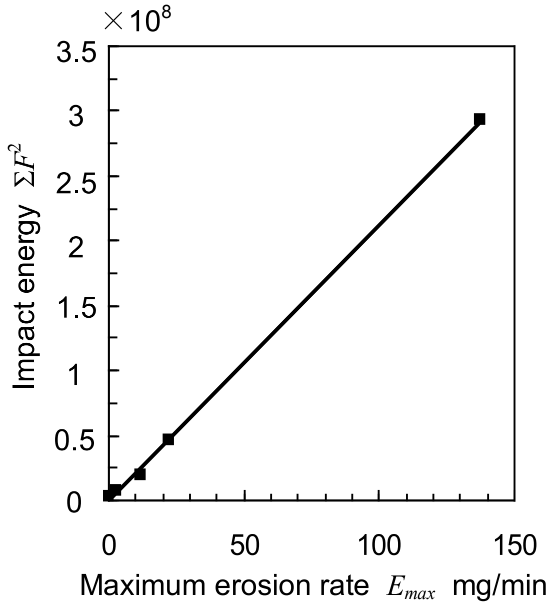


Fig. 9 Relation between impact energy and maximum erosion rate

In order to investigate the peening region of the cavitating jet at d = 2 mm, p_1 = 30 MPa and d = 0.35 mm, p_1 = 300 MPa, Fig. 7 reveals the distribution of the residual stress across the test specimen by using 2D method. For both cases, the compressive residual stress about 200 MPa was introduced from y = -20 mm to 20 mm. In the case of d = 0.35 mm, the nozzle throat was considerably small, however, the cavitation was developed as p_1 = 300 MPa. Thus, the jet can introduce compressive residual stress 40 mm in width. As shown in Fig. 7, the width of d = 2 mm, p_1 = 30 MPa was wider than that of d = 0.35 mm, p_1 = 300 MPa. Namely, in view point of treatment area, the jet of d = 2 mm, p_1 = 30 MPa would be better.

In order to investigate the reason of above mentioned results, Fig. 8 shows the distribution of impact energy measured by the PVDF sensor. When the threshold level was considered [15], the measured impact energy was proportional to the erosion rate, i.e., the ability of the jet as shown in Fig. 9. It was obvious that the impact energy of d = 2 mm, p_1 = 30 MPa was considerably larger than that of d = 0.35 mm, p_1 = 100 and 200 MPa.

Conclusions

In order to find optimum condition of a cavitating jet for cavitation peening, the residual stress treated by the cavitating jet at various nozzle throat diameter d and the injection pressure p_1 was evaluated by X-ray diffraction methods, i.e., $\sin^2\psi$ method and 2D method. The tested material was stainless steel JIS SUS316L. It was concluded that the large cavitating jet at low injection pressure such as d = 2 mm and p_1 = 30 MPa introduced larger compressive residual stress into deeper region, comparing the small jet at high injection pressure such as d = 0.35 mm and p_1 = 300 MPa.

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